Strontium isotope analysis to reveal migration in relation to climate change and ritual tooth ablation of Jomon skeletal remains from western Japan

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Abstract

A gradual population increase accompanying climate cooling has been evinced as having occurred in western Japan during the Middle (ca. 5000–4000 years BP) to Late-Final Jomon period (ca. 4000–2300 years BP). We test the hypothesis that this population change paralleled increasing human migration. We also test the archaeological hypothesis that types of ritual tooth ablation can be used to distinguish between locals and immigrants during the Late-Final Jomon period. We measured strontium isotope ratios in human skeletal remains from the Middle Jomon Ota and the Late-Final Jomon Tsukumo sites located in the Sanyo region of western Japan. Tooth enamel and bone were analyzed, and modern plant samples were collected in the areas surrounding the two sites to make a map of environmental strontium isotope ratios. The biosphere strontium isotope ratios correlated well with the underlying geology, enabling us to put forth a hypothesis of immigrants' origins. There were no migration pattern differences between the Middle and Late-Final Jomon groups, indicating that the gradual population increase was caused by an increase in the indigenous population. All the Tsukumo individuals are locals, and this finding indicates that types of tooth ablation did not distinguish between locals and immigrants. Alternative hypotheses for the presence of different tooth ablation types in the Jomon society should be explored.

Key words: Tooth enamel, strontium isotope, Jomon period, Japan, hunter-gatherers, tooth ablation.

Introduction

Strontium isotope analysis of human skeletal remains is a useful tool in identifying immigrants and assessing human migration in ancient societies. This method has been well established (Bentley, 2006), and has been applied a number of times to investigate past human migrations, such as in the Pueblo people in North America (Price et al., 1994b; Ezzo et al., 1997; Ezzo and Price, 2002), the Bell Beaker and Linearbandkeramik people in Central Europe (Price et al., 1994a; Grupe et al., 1997; Price et al., 1998; Bentley et al., 2004), the Iceman (Müller et al., 2003) at West Heslerton in England (Montgomery et al., 2005), in Mesoamerica (Price et al., 2010; Wright et al., 2010), in the Andes of South America (Knudson et al., 2004; Knudson and Torres-Rouff, 2009), at Machu Picchu in Peru (Turner et al., 2009), at Khok Phanom Di in Thailand (Bentley et al., 2007), and in the Lapita populations in Papua New Guinea (Shaw et al., 2009, 2010). Recently, it has been applied to detect migration among hunter-gatherers (Tafuri et al., 2006; Haverkort et al., 2008; Kusaka e al., 2009, 2011; Stojanowski and Knudson, 2011). This study demonstrates strontium isotope analysis on Jomon (Japanese Neolithic) skeletal and dental remains to identify immigrants in two populations. The samples are skeletal and dental remains from the Ota shell mound of the Middle Jomon period and the Tsukumo shell mound of the Late-Final Jomon period (Fig. 1). Two hypotheses were tested. The first is that the proportion of immigrants increased through the Middle to Late-Final Jomon period due to climate change. The second is that types of ritual tooth ablation of the Late-Final Jomon period can be used to distinguish between locals and immigrants.

Jomon population in Japan

The Jomon culture, which is characterized by cord-marked pottery, lasted from 13000 to 2300 years BP in the Japanese Archipelago (Habu, 2004; Imamura, 1996). Generally speaking, the Jomon people were sedentary hunter-gatherers who effectively exploited marine and terrestrial resources. Their diet of prehistoric populations is an important indicator of how they subsisted and adapted to the environment. The composition of the Jomon people's diet can be inferred from excavated faunal and floral remains. They mainly hunted deer, boar, and other small mammals (Kaneko, 1994). They caught many kinds of fish, shellfish, and marine mammals in the coastal environment (Kaneko, 1980). The majority of plant remains are chestnuts, walnuts, and acorns that are stored in ground pits (Watanabe, 1975). At least a few domesticated plants were commonly used after the Early Jomon period, including egoma, shiso mint, and others (Habu, 2004). Jomon subsistence strategies followed the seasonality of each food resource (Nishida, 1980; Akazawa, 1986; Kobayashi et al., 2004). In spring, they gathered leaf stems, shells, and seaweed. In summer, they engaged in fishing activities. In autumn, they gathered nuts and fruits. In winter, they hunted deer and boar.

Climate change would have affected the population and people's subsistence during the Jomon period. Pollen analysis has revealed climatic warming after the last glacial period. The time from 7000 to 4000 years BP was the warmest period of the last 20000 years BP, and vegetation was in equilibrium (Tsukada, 1986). Western Japan was characterized by warm-temperate evergreen forests, and eastern Japan by cool-temperate forests. In that time, the population in the Japanese archipelago gradually increased, and eastern Japan had a higher population than western Japan (Koyama, 1978). Climatic cooling occurring from 4000–1500 years BP has been demonstrated by pollen analysis (Tsukada, 1986), and has been associated with population decline in inland and eastern Japan during the Late-Final Jomon period (Koyama, 1978). This depopulation might have been caused by lower yields from plant resources in the colder environment. In contrast, a gradual population increase has been found in western Japan from the Middle to Late-Final Jomon period. Systemic stress and food changes that accompanied the cooling climate have been identified. Temple (2007) revealed that the frequency of tooth caries was higher in the Late-Final Jomon group than in the Middle Jomon group, implying that the Late-Final Jomon people shifted to a plant-based diet. Kusaka et al. (2010) found that the Late-Final Jomon group ate less marine and freshwater fish than did the Middle group.

Climate change might have caused the Jomon people to adjust their subsistence regimes and to disperse to surrounding areas (Habu, 2004). Archaeological analysis of sites in western Japan revealed that large settlements were disbanded and people aggregated to small settlements from the Middle to Late-Final Jomon period (Okamoto, 1987; Hirai, 1987). In the warm temperatures of the Middle Jomon period, larger and more sites appeared. Fishing occupied a large part of subsistence, and large shell mounds accumulated. In the Late-Final Jomon period, there were even more sites, but they were smaller (Okamoto, 1987). Hirai (1987) proposed that the coastline changed because of alluvial deposition. In this changing environment, fishing activities recessed, and marine food was depleted. This caused large settlements to disperse and people aggregated in coastal areas, although some would have moved inland (Okamoto, 1987; Hirai, 1987). People would have selected superior places to live where much food could be acquired, and the smaller population could obtain sufficient food even in the deteriorated environment.

Geology of the Sanyo region

Late Paleozoic to Jurassic accretionary complexes and their metamorphic equivalents make up the Inner Zone of Southwest Japan. Maizuru (Permian mudstone and basalt) and Tamba Belts (Jurassic sedimentary complexes) lie in the field running from the north to the south of the Sanyo region (Fig. 2). Mudstone and basalt lava of the Maizuru Belt are distributed in the northern part of the field. The strontium isotope ratio of the metabasalt was reported by Koide et al. (1987) to range from 0.704–0.707. The mudstone of the Tamba Belt is distributed in the southern and western parts of the field. Cretaceous-Paleogene granitic and volcanic rocks are intruded into the sedimentary complex. Granitic rock type III (Late Cretaceous) is widely distributed. Kagami et al. (1988) reported its strontium isotope ratio as being 0.7107. The strontium isotope ratio of the Takada rhyolites (Late Cretaceous) is 0.706–0.709 (Matsumoto et al., 2001). Permian limestone is distributed in the inland area where rock shelter sites were found. Its strontium isotope ratio is 0.707–0.708 (Tazaki et al., 1989) which is in accordance with Permian seawater values (McArthur et al., 2001). The strontium weathered from these rocks is the principal contributor of strontium in the biospheres and determines the regional strontium isotopic distribution.

Figure 2 indicates the distribution of Jomon sites in the Sanyo region divided by period. Many sites are located along the coast, and two rock shelter sites lie inland. There are less Middle Jomon period sites than Late-Final Jomon period sites, although some were used continuously from the Middle period through the Late-Final Jomon period. This study focused on two sites, Ota and Tsukumo, which are large shell mounds in the coastal area from the Middle and Late-Final Jomon period, respectively. Since the ages of the two sites are different, we tested the hypothesis that the Late-Final Jomon group in western Japan might have received more migrants than the Middle Jomon group, paralleling a gradual population increase. Strontium isotope analysis of human skeletal remains can identify immigrants who have grown up and migrated to an isotopically different region. Although both Ota and Tsukumo are located on granitic rocks, mudstone and basalt of the Maizuru Belt are also distributed within a 10 km radius from the sites. This complex geology makes it difficult to predict local strontium isotope ratios for their inhabitants. We measured the strontium isotope ratios of plants to investigate biosphere strontium isotopic distribution. For the Ota site of the Middle Jomon period, some coastal sites and an inland site are likely immigrants' original homes because they belong to the same period. For Tsukumo site of the Late-Final Jomon period, there are many coastal sites as well as some inland sites that are likely sources of immigrants.

Ritual tooth ablation

Ritual tooth ablation in a variety of patterns was widely practiced among the Jomon people during the Late-Final Jomon period (e.g., Watanabe, 1966; Harunari, 1979, 1986, 2002). Tooth ablation is thought to have been a customary component of coming-of-age ceremonies, based on estimated age at the time of tooth ablation (Hasebe, 1919; Watanabe, 1966; Fujita, 1997). Patterns in tooth ablation might provide invaluable information on the social organization of the Jomon people, and several different hypotheses have been proposed regarding the practice. The most influential hypothesis explaining variations in Jomon tooth ablation patterns was formulated by Harunari (1973, 1979). He categorized tooth ablation through observation of skeletal remains from the Tsukumo and Yoshigo shell mounds in the following way: Extraction of two maxillary canines is called type 0. Type 4I indicates the extraction of two maxillary canines and four mandibular incisors, while type 2C is the extraction of two maxillary and two mandibular canines.

Type 0 is considered a coming-of-age ceremony because almost all individuals extracted these canines (Harunari, 1973, 1979). Ritual tooth ablation is not related to sex or age at death of skeletal remains. Because tooth ablation types in grave clusters and double inhumations tend to lean toward type 4I or 2C tooth ablation in the Yoshigo and Inariyama shell mounds, tooth ablation types are regarded to be symbols of social relationships within a group. Taiwanese ethnographic data has documented that tooth ablation was performed when a male and female married. Harunari (1979) proposed that tooth ablation was also performed when the Jomon people married and that tooth ablation patterns were associated with the distinction between locals and immigrants. Since type 4I skeletons tended to be buried with personal offerings and included many individuals with tooth filing on their incisors, he hypothesized that these were locals of high prestige. He suggested that type 2C individuals were immigrants married to type 4I individuals. This hypothesis further indicates postmarital residence of the Jomon people. Since there are approximately equal numbers of male and female type 4I and type 2C individuals in the Yoshigo and Inariyama skeletal remains of the Tokai region, Harunari (1979) suggested that both males and females migrated between populations to marry indigenous people, implying bilocal residence. The hypothesis has been assessed using several physical anthropology methods. A cranial nonmetric trait study provided support for the hypothesis (Mouri and Oku, 1998). Kusaka et al. (2008) found that dietary patterns were associated with tooth ablation types in the Inariyama skeletal remains. Previous research on the relationship between migration pattern and tooth ablation types established that both type 4I and type 2C individuals migrated between populations (Kusaka et al., 2009, 2011). Since information about the Late-Final Jomon group used in this study is the fundamental material that contributes to the construction of the theory that tooth ablation types imply migration, further analysis would be valuable in testing whether the hypothesis is valid.

We tested two hypotheses using strontium isotope analysis. The first is that the proportion of immigrants increased through the Middle up to the Late-Final Jomon period. This can be tested by comparing the frequencies of immigrants identified by their strontium isotope ratios between the Middle Jomon and the Late-Final Jomon groups. The second hypothesis is that there is a significant relationship between migration pattern and tooth ablation types in the Late-Final Jomon group. That is, type 4I individuals are locals, and they married type 2C immigrants. This hypothesis will be tested by comparing frequencies of immigrants in the two tooth ablation groups and by comparing mean strontium isotope ratios of the two tooth ablation groups.

Strontium isotope analysis

Strontium (Sr) is a member of the alkaline earth elements. The ionic radius of Sr^{2+} (1.13 Å) is slightly larger than that of Ca^{2+} (0.99 Å). Strontium occurs in Ca-bearing minerals such a plagioclase, apatite, and calcium carbonate, especially aragonite (Faure and Mensing, 2005). Strontium has four stable isotopes (^{88}Sr, ^{87}Sr, ^{86}Sr, and ^{84}Sr). Their isotopic abundances are approximately 82.53%, 7.04%, 9.87%, and 0.56%, respectively. The abundances of strontium isotopes are variable because of the formation of radiogenic ^{87}Sr by the decay of naturally occurring ^{87}Rb. For this reason, the isotopic composition of strontium in a rock or mineral that contains Rb depends on the age of formation and initial Rb/Sr ratio of that rock or mineral. Because the half-life of ^{87}Rb is 4.88×10^{10} years, there has been essentially no change in the ^{87}Sr/^{86}Sr value of natural materials in the last several hundred thousand years. The average concentrations of strontium in different kinds of igneous and sedimentary rocks range from 1 ppm in ultramafic rocks to about 465 ppm in basaltic rocks and reach very high values in carbonate rocks (up to 2000 ppm or more; Faure and Mensing, 2005). Continental crust with a high Rb/Sr ratio (e.g., granite) has an average ^{87}Sr/^{86}Sr of 0.716, while oceanic basalt with a low Rb/Sr ratio has an average ^{87}Sr/^{86}Sr ratio of 0.703 (Bentley, 2006). Phanerozoic marine limestone and dolomite have intermediate ^{87}Sr/^{86}Sr values of about 0.707–0.709, reflecting the composition of the ocean during their deposition (Hess et al., 1986).

Strontium in rocks is released by weathering, cycled through soils, groundwater, vegetation and animals, and eventually enters the oceans as sediment by river transport (Graustein and Armstrong, 1983; Åberg, 1995; Capo et al., 1998). The strontium isotopic composition of animals and plants faithfully reflects the isotope composition of the rocks and soil where they live and grow, because the biologically available strontium derived from rocks and soil is incorporated by biosynthetic processes and passed up food chains (Graustein, 1989; Blum et al., 2000). Isotopic fractionation through these processes is negligible because of the large atomic mass of strontium, meaning that the ratio of ^{87}Sr to ^{86}Sr does not change. In addition, any possible fractionation in ^{87}Sr/^{86}Sr would be corrected for in mass spectrometry by normalizing to a constant ^{86}Sr/^{88}Sr ratio of 0.1194 (Beard and Johnson, 2000). The variance of Sr/Ca ratios decreases going up the food chain (Elias et al., 1982), and reduced variance due to biopurification is also found in ^{87}Sr/^{86}Sr values of plants and animals (Blum et al., 2000).

The $^{87}Sr/^{86}Sr$ variation in skeletal tissues is less than that of soils and plants. This is because herbivores consume a mixed diet of plants from their local area, and the $^{87}Sr/^{86}Sr$ values in their diet average out over the time their bones form (Bentley, 2006). Generally, large $^{87}Sr/^{86}Sr$ variations are observed in the bones of animals that lived in a geologically diverse area, such as elephants and birds, and small $^{87}Sr/^{86}Sr$ variations are found in bones of small mammals and domestic animals because they usually have relatively smaller home ranges than larger mammals or their wild counterparts (Price et al., 2002).

In humans, the $^{87}Sr/^{86}Sr$ signature in tooth enamel is an excellent archive of strontium from the area where a person resides during childhood. Tooth enamel does not remodel after its formation during childhood. Thus, if an individual migrated between geologically contrasting residential areas, the strontium isotope signatures in his or her tooth enamel would differ from his or her bones, which would come to conform to from the new area of residence, as well as from the strontium isotope ratios in the soil, plants, and animals of the local region (Bentley, 2006). If people migrate between geologically similar areas, the strontium isotope analysis cannot identify immigrants. Since humans are omnivorous, the strontium isotope ratio of tooth enamel is a weighted average of their food sources (Montgomery, 2010). The $^{87}Sr/^{86}Sr$ ratios of individuals who consumed terrestrial resources should be close to those of local plants and animals. Since the strontium level in meat is lower than that in plants, dietary strontium comes primarily from plants in terrestrial diets. The strontium isotope ratio of seawater has varied over geologic time (McArthur et al., 2001), but it can be assumed to have stayed the same (0.7092) for the last 10000 years. Marine organisms incorporate strontium from seawater, and have the same $^{87}Sr/^{86}Sr$ values as seawater. Ingestion of mollusks results in high levels of strontium in bones, like eating plants, because mollusks contain a large amount of strontium (Schoeninger and Peebles, 1981). Thus, the $^{87}Sr/^{86}Sr$ levels in the bones and teeth of individuals who consumed marine foods are expected to be similar to seawater (Montgomery et al., 2007). The $^{87}Sr/^{86}Sr$ values of plants and animals are also subject to sea-spray, which is an important source of soil nutrients (Whipkey et al., 2000). Moreover, sea salt is an important alkaline earth intake because salt has high levels of calcium and strontium. Wright (2005) revealed that the $^{87}Sr/^{86}Sr$ values of sea salt significantly elevated the signature of a local population above the values of local terrestrial plants. This results from strontium uptake in maize treated with a lime solution in the Maya region. Since consumption of marine resources and sea salt significantly affect the $^{87}Sr/^{86}Sr$ values of bones and teeth, it is important to consider possible strontium sources in the diet of an archaeological population, particularly marine strontium in coastal areas.

Defining local strontium signatures

A challenge involved in strontium isotope analysis of human skeletal remains is how to define local strontium signatures: that is, what are the levels of biologically available strontium for site inhabitants (Bentley et al., 2004; Price et al., 2002)? Several methods have been used. Characterization of local $^{87}Sr/^{86}Sr$ signatures using environmental and faunal samples has been done in previous studies. Sillen et al. (1998) suggested the importance of utilizing plants or water that animals consume in the local area rather than rock or soil. Hodell et al. (2004) examined the spatial variation of strontium values in the Maya area using water and plant samples. The Maya area presented distinct $^{87}Sr/^{86}Sr$ values in each region, associated with geologic structures. Based on these data, Wright (2005) successfully identified immigrants to the ancient Maya city of Tikal. Biosphere $^{87}Sr/^{86}Sr$ mapping was also attempted in Skye, Scotland to produce reference datasets for tracking material movements or animal and human migrations (Evans et al., 2009). Kusaka et al. (2009, 2011) also illustrated biosphere $^{87}Sr/^{86}Sr$ mapping in the Tokai region of Japan to identify immigrants in the Jomon population. Uncovering the spatial variation of strontium isotope ratios is useful not only to identify immigrants, but also to estimate their origins. Strontium isotope ratios of plants generally vary more than those of animals, so archaeological faunal values are recommended to define the local $^{87}Sr/^{86}Sr$ range (Price et al., 2002).

The other method of identifying immigrants in a population is to evaluate the statistical coherence of the strontium isotopic data (Wright, 2005). The optimum approach assumes that the $^{87}Sr/^{86}Sr$ values of local individuals would fall in a normal distribution if they were born and grew up in an area and consumed the same foods, also grown in the local area. A similar approach was also adopted for a population in the Cuzco Valley of Peru (Andrushko et al., 2009) and from Conchopata in Peru (Tung and Knudson, 2011). We present a case where strontium isotope analysis is used to study the Jomon hunter-gatherers that lived in the coastal environment of Japan.

Materials

Two human skeletal populations in the Sanyo region of Japan were selected for this study. The Ota shell mound in Onomichi City, Hiroshima Prefecture was excavated in 1926 (Fig. 1). The skeletal remains of 55 individuals were found together with stone tools and Jomon pottery (Kiyono, 1969). The skeletal remains of the Ota site have been dated to the Middle Jomon period (ca. 5000–4000 years BP) by pottery types (Shiomi et al., 1971). Twenty-three human tooth enamel and five rib samples were used for strontium isotope analysis (Table 1). The Tsukumo shell mound in Kasaoka City, Okayama Prefecture, was excavated in 1920–1922. Seventy-two individuals were found and dated to the Late-Final Jomon period (ca. 4000–2300 years BP). Most of the individuals are well preserved so that their sex and age can be confidently estimated. Thirty-seven human tooth enamel and seven rib samples from the Tsukumo population were used for strontium isotope analysis. The age and duration of the site formation are not documented for these sites since the excavations were conducted in the early 1920's. A large amount of temporal variation might limit the interpretation of this study. In the future, radiocarbon dates of skeletal remains would resolve the problem of temporal variation.

One of the authors (S. K.) determined the sex of subject individuals from their hipbones (Phenice, 1969) and cranial features (Buikstra and Ubelaker, 1994), and their age at death from the morphologies of the pubic symphysis (Brooks and Suchey, 1990), the auricular surface of the ilium (Lovejoy et al., 1985), cranial sutures (Meindl and Lovejoy, 1985), and dental attrition (Lovejoy, 1985). Age at death of the human skeletal remains examined in this study was categorized into the following ranges: adolescents (12–20 years), young adults (20–35 years), and middle adults (35–50 years; Buikstra and Ubelaker, 1994).

The samples are housed in the Laboratory of Physical Anthropology, Department of Zoology, Graduate School of Science, Kyoto University. Third molars and ribs were sampled. Third molars form during the period from 9–13 years of age (mean) of an individual, but the range varies: cusp formation begins at 7–12 years old, and crown formation is complete at 10–17 years (Hillson, 1996). Tooth enamel matures for several months to a year after formation (Montgomery and Evans, 2006). As mentioned above, tooth enamel in third molars retains strontium acquired from the diet during late childhood to early adolescence. Bone reflects the values of $^{87}Sr/^{86}Sr$ averaged over the last 10 years or so of an individual's lifetime, because the turnover time of bone is 10 years or more (Stenhouse and Baxter, 1979). This dietary signature in bone, however, could be modified by diagenetic alterations, as discussed later. We collected plant samples from 42 locations in the field around the sites, recording their locations using GPS (Fig. 3A; Table 2).

Methods

Strontium isotope analysis

Human tooth and bone samples were ultrasonically cleaned in ultrapure water and then dried. A dental drill equipped with a diamond burr and a tungsten carbide burr was used to abrade the tooth enamel and bone samples. After abrading the surfaces to remove soil-derived substances, we collected 5-mg samples of enamel and of compact bone from the ribs.

The strontium isotope analyses, including the pretreatment steps, were performed at the Research Institute for Humanity and Nature. Buffered acetic acid solution (0.1 M, pH = 4.5, 1 ml) was used to eliminate diagenetic contaminants from the enamel and bone samples (Sillen, 1986; Hoppe et al., 2003; Trickett et al., 2003) as follows. First, the samples were agitated for 10 minutes in the acetic acid solution and centrifuged, and then the supernatant was discarded. This procedure was performed twice. Then, the samples were agitated another 10 minutes and centrifuged, and the supernatant was retained for measurement. Each plant sample (0.5 g; ashed in a muffle furnace at 650 °C for 24 hours) was placed in a centrifuge tube with ultrapure water (10 ml) and then left overnight. After centrifugation, the supernatant was used as the sample solution.

All sample solutions were dried in Teflon® vials on a hotplate. Then HNO_3 (14 M) was added, and the vials were left on the hotplate at 200 °C to decompose organic matter. The samples were then dissolved in HCl (2 M), and strontium was separated chromatographically using a cation exchange resin (DOWEX®, 50 × 8, 200–400 mesh). Strontium isotope ratios were measured on a degassed tungsten filament with a TRITON thermal ionization mass spectrometer (Thermo Fisher Scientific). Sample $^{87}Sr/^{86}Sr$ data was normalized, consistent with the standard reference NIST SRM 987 (0.710250; Faure and Mensing, 2005). For Ota and Tsukumo strontium isotope data, internal precision based on counting ions 100 times was ± 0.000004–0.000008 (= 1 standard error). External precision determined by repeated measurements (n = 48) of NIST SRM 987 was ± 0.000005 (= 1 standard deviation [SD]) with a mean of 0.710257 over all measurements conducted in a period of six months.

Statistical analysis

The *F*-test was used to evaluate whether the variations of bone and enamel strontium isotope ratios were equal. The Shapiro–Wilk test, which is an excellent method of assessing normality, was used to evaluate whether the enamel strontium isotope ratios were normally distributed (Zar, 1999). To find outliers from samples with non-normal distributions, Chauvenet's criterion, which evaluates whether or not a data point is an improbable member of a distribution, was used (Taylor, 1982). The *t*-test was used to evaluate whether the mean strontium isotope ratios of enamels are different between type 4I and type 2C individuals from the Tsukumo site. Statistical analysis was performed using JMP 6 software (SAS institute) and SPSS 19 (IBM). Statistical significance was evaluated as $P < 0.05$.

Results

Geological variation and geographic ^{87}Sr/^{86}Sr distribution in plants

The plant samples collected from the field (n = 42) had a mean ^{87}Sr/^{86}Sr value of 0.70909 ± 0.00090 (mean ± 1 SD) with a range of 0.71071–0.70696 (Table 3). The plant ^{87}Sr/^{86}Sr values shows a regional cline decreasing from west to east (Fig. 3B). This cline correlates well with the surface geology. Late Cretaceous granitic rocks (0.7107) are extensively exposed in the west, whereas mudstone and basalt lava of the Maizuru group (0.704–0.707) are distributed in the eastern and northern areas. However, this regional cline is weaker in the area along the coast than in the inland area (Fig. 3B). Marine strontium derived from sea spray would affect the strontium isotope ratios of plants along the coast.

Strontium isotope ratios within a radius of 10 km of a site are indicative of those of the terrestrial sources used by a local population. The mean strontium isotope ratio of plants within a radius of 10 km of the Ota shell mound was 0.70950 ± 0.00081 (n = 11) with a range of 0.70847–0.71071. The mean strontium isotope ratio of plants within a radius of 10 km of the Tsukumo shell mound was 0.70922 ± 0.00068 (n = 11) with a range of 0.70780–0.71014. Since the ranges of plant ^{87}Sr/^{86}Sr values of two sites overlap, strontium isotope analysis cannot identify immigrants who migrated between the two areas. The overlapping of the ranges of plant ^{87}Sr/^{86}Sr values of the two sites occurs because of the complex geology around the two sites that is composed of granitic rocks and basalt, and the effect of sea spray. However, plant ^{87}Sr/^{86}Sr values in the northeastern part of the field, where mudstone and basalt lava are distributed, are 0.707–0.708. The plant ^{87}Sr/^{86}Sr value in the western part of the field, where Late Cretaceous granitic rocks are distributed, is 0.710. Immigrants originating from these areas can be identified through strontium isotope analysis.

Strontium isotopes in skeletal and dental remains from the Ota and Tsukumo sites

The mean strontium isotope ratio in the human tooth enamel of the Ota samples (n = 23) was 0.70891 ± 0.00010 (mean ± 1 SD) with a range of 0.70855–0.70903 (Fig. 4). The human bone samples (n = 5) had a mean ^{87}Sr/^{86}Sr ratio of 0.70886 ± 0.00004 with a range of 0.70882–0.70892. The mean strontium isotope ratio in the human tooth enamel of the Tsukumo samples (n = 37) was 0.70889 ± 0.00016 with a range of 0.70849–0.70925 (Fig. 5). The human bone samples (n = 7) had a mean ^{87}Sr/^{86}Sr ratio of 0.70880 ± 0.00008 with a range of 0.70871–0.70897. The range in the bone samples is narrower than the range of ^{87}Sr/^{86}Sr ratios in the tooth enamel samples from both sites. There is no statistically significant difference between the strontium isotope ratios of the type 4I and type 2C individuals from Tsukumo (*t*-test, $t = 0.120$, $P = 0.905$).

Tooth enamel suffers much less diagenetic contamination than bone (Hoppe et al., 2003; Trickett et al., 2003). Strontium isotopic records in bone hydroxyapatite are generally susceptible to diagenetic alteration because of the relatively porous crystal structure of bone hydroxyapatite (Sillen, 1986; Hoppe et al., 2003; Trickett et al., 2003). As discussed below, most of the enamel samples exhibited the same values as plants around the sites. This might indicate that most of the samples were contaminated with diagenetic strontium from burial in soil and from water. However, diagenetic contamination that exists in the secondary minerals of enamel and bone can be removed by leaching with weak acid (Hoppe et al., 2003; Trickett et al., 2003). We interpret that the enamel ^{87}Sr/^{86}Sr values are biogenic, because the enamel surfaces were abraded and leached with weak acid, which would eliminate any diagenetic strontium, while bone ^{87}Sr/^{86}Sr values reflect both biogenic and diagenetic strontium.

Discussion

Assessing plant ^{87}Sr/^{86}Sr values

To distinguish immigrants from locals, it is necessary to delimit the local ^{87}Sr/^{86}Sr range. Because the foraging area of modern hunter-gatherers is generally within 10 km of their settlement (Binford, 2001), we consider strontium isotope ratios within a radius of 10 km of the sites to be indicative of those of terrestrial sources used by a local population. The minimum to maximum ^{87}Sr/^{86}Sr values of plants within a radius of 10 km of the Ota shell mound ranged between 0.70847–0.71071. The minimum to maximum ^{87}Sr/^{86}Sr values of plants within a radius of 10 km of the Tsukumo shell mound were 0.70780–0.71014. Any enamel strontium values that fall out of these ranges might suggest migration. All of the enamel samples from the two sites were within the local strontium ranges and all individuals were identified as locals. However, we must not overlook the fact that the variation of strontium isotope ratios of plants is generally larger than that of humans, since the strontium isotope ratio of a human skeleton is an average of what the individual consumed. Thus, another method was used to identify immigrants as discussed below.

Statistical assessment of enamel ^{87}Sr/^{86}Sr values

To identify immigrants, we also evaluated the statistical coherence of enamel strontium isotope values. Wright (2005) suggested that one might expect skeletal ^{87}Sr/^{86}Sr values to be normally distributed at an archaeological site where there is good reason to believe that the majority of the population were born and grew up locally and that all individuals consumed foods grown on the same soils. Unfortunately, we do not have any data to estimate how much food was shared and exchanged within the Jomon population. However, it is largely accepted that food sharing within a community is fundamental to hunter-gatherer subsistence economies (Bird, 1999). When their subsistence is taken into account, it seems improbable that they consumed much food imported from other areas. Thus it can be assumed that the ^{87}Sr/^{86}Sr values of Jomon hunter-gatherers in these sites also present a normal distribution.

Table 4 contains summary statistics for all the Ota samples. The strontium isotope ratios of all the samples exhibit a negative skew and positive kurtosis, indicating a significant deviation from a normal distribution. Figure 6 shows the histogram of Ota's "all" data set (n = 23) with an estimated normal distribution curve for comparison. One individual (No. 697) stands out as a possible outlier. The null hypothesis that all samples take a normal distribution was rejected by the Shapiro–Wilk test for normality ($W = 0.792$, $P < 0.001$). Chauvenet's criterion can be used to evaluate whether or not a data point is an improbable member of a distribution (Taylor, 1982). The lowest data point is lower than the average by 3.6 standard deviations, and it is regarded as an outlier based on Chauvenet's criterion. Thus, sample No. 697 was regarded to be an immigrant to the Ota population.

Table 4 also contains a statistical summary of the Ota "local" data set (n = 22), from which the immigrant data is excluded. The data set of locals displays a smaller variation with smaller skewness and kurtosis. The Shapiro–Wilk test does not reject the hypothesis that the local samples take a normal distribution (W = 0.959, P = 0.469). The statistical evaluation of strontium isotope signatures indicates that the Ota individuals examined consisted of one immigrant and other local members.

The strontium isotope ratios of the immigrant indicate candidate zones where the immigrant settled during late childhood and adolescence. Ota immigrant No. 697 had an $^{87}Sr/^{86}Sr$ value of 0.7085. This lowest $^{87}Sr/^{86}Sr$ value suggests less seafood consumption. This individual might have grown up in an area where the mudstone and basalt of the Maizuru Belt (0.704–0.707) and the Takada rhyolites (0.706–0.709) are extensively exposed, particularly in the northeastern part of the field. The inland site (Taishaku Kannondo) where Permian limestone (0.707–0.708) is exposed is also a possible area of origin for the immigrant.

The statistical coherence of enamel strontium isotope values of the Tsukumo samples was also evaluated. The distribution of the $^{87}Sr/^{86}Sr$ values of the Tsukumo samples is not skewed (Table 4). The Shapiro–Wilk test does not reject the hypothesis that the Tsukumo samples are a normal distribution (W = 0.966, P = 0.319). The normal distribution of the Tsukumo samples indicates that all individuals are locals.

Comparing migration between the Middle and Late-Final Jomon periods

The proportion of immigrants in Ota (4%) is about as low as that of Tsukumo (0%). This result rejects the first hypothesis that the proportion of immigrants increased from the Middle Jomon period through the Late-Final Jomon period in the Sanyo region. Climatic cooling through the Middle Jomon period to the Late-Final Jomon period would have changed the environment for the Jomon population. Cooling temperatures might have reduced vegetation yields (Hirai, 1987). Food was depleted for the large population at the end of the Middle Jomon period, which could have been resolved by dispersing into smaller populations (Okamoto, 1987; Hirai, 1987). Our results indicate that once many small settlements were distributed in the Late-Final Jomon period, people might not have migrated frequently. Another possibility is that people actually migrated, but between isotopically similar regions. Strontium isotope ratios in plants vary considerably around the Ota and Tsukumo sites, which lie in areas with complex geology, resulting in overlapping mean strontium isotope ratios in the plants around the two sites. Plants grown in the coastal area would be influenced by marine strontium, which makes the strontium isotope ratios in plants close to 0.7092. Seafood consumption also contributed to be marine signatures in the enamel strontium isotope ratios. These might mask human migration between populations in the coastal areas of the Sanyo region, but migration between coastal and inland areas would be visible from strontium isotope ratios of tooth enamel.

These results contrast with previous studies that have focused on the Tokai region of central Japan, in which higher proportions of immigrants were identified in the Late-Final Jomon sites (Kusaka et al., 2009, 2011). Thirty-six percent of individuals were identified as immigrants at the Yoshigo shell mound, which was dated from the later part of the Late Jomon period to the Final Jomon period (ca. 3500–2300 BP; Kusaka et al., 2009). Twenty-four percent of individuals were identified as immigrants at the Inariyama shell mound, which was dated far into the Final Jomon period (ca. 3000–2300 BP; Kusaka et al., 2011).

These contrasting results may allow two interpretations. First, the proportion of immigrants may have actually increased from the Middle Jomon through the Late-Final Jomon period. Changes in the systemic stress level and diet of the Jomon people associated with climatic cooling ca. 5000 years BP were also observed. The frequency of tooth caries is higher in the Late-Final Jomon group than the Middle Jomon group, implying that the Late-Final Jomon group shifted to a plant-based diet (Temple, 2007). Carbon and nitrogen stable isotope analysis revealed that the Middle Jomon group ate much more marine and freshwater fish than the Late-Final Jomon group (Kusaka et al., 2010). Climatic cooling from the Middle to Late-Final Jomon period might have coincided with changes in stress levels, dietary consumption, and migration.

Second, migration between populations may have occurred more frequently in the Tokai region (Yoshigo and Inariyama) than in the Sanyo region (Ota and Tsukumo). Regional differences are also observed in enamel hypoplasia frequency and diet. The frequency of enamel hypoplasia is higher in the western Jomon group than the eastern Jomon group, implying that the population in western Japan subsisted on a plant-based diet or suffered from seasonal food depletion (Temple, 2007). Nitrogen isotope ratios of individuals from the Sanyo region were significantly higher than ratios of individuals from the Tokai region (Kusaka et al., 2010). The individuals in the Sanyo region might have consumed a diet high in aquatic foods, particularly high trophic level marine fish, whereas the individuals in the Tokai region might have consumed a lot of marine shellfish. The depopulation in eastern Japan during the Late-Final Jomon period might have led to population dispersal and aggregation in the Tokai region, which contributed to its high proportion of immigrants. The gradual increase in the population in western Japan might not have been caused by dispersal, but by an indigenous population growth with a low level of human migration. To reach a conclusion, we will have to investigate samples from the Middle Jomon period of the Tokai region to further research age differences in migration patterns in each region.

Migration and ritual tooth ablation

Differences in ritual tooth ablation type have been hypothesized to be a marker distinguishing between locals and immigrants among a population of the Late-Final Jomon period (Harunari, 1979). This hypothesis was tested by comparing the proportion of immigrants and strontium isotope values between tooth ablation groups of Tsukumo individuals. We did not find any immigrants based on the strontium isotope ratio. When comparing strontium isotope ratios of type 4I and type 2C individuals, there is no significant difference (Fig. 7). This means there is no difference in the geographic origins of type 4I and 2C individuals. These results do not support the hypothesis that type 2C individuals are immigrants and type 4I individuals are locals. Previous strontium isotope analyses revealed that type 4I and type 2C individuals include locals and immigrants with a slightly higher proportion of immigrants among type 2C (Kusaka et al., 2009, 2011). Overall these results do not seem to favor the hypothesis that tooth ablation types have a significant relationship with migration patterns. It is generally agreed that tooth ablation was done as a coming-of-age ceremony (Hasebe, 1919; Watanabe, 1966; Fujita, 1997). The typology of ritual tooth ablation indicates additional meanings. Tooth ablation types were associated with dietary patterns in Inariyama: Type 2C individuals were more dependent on marine foods than type 4I individuals (Kusaka et al., 2008). Such findings might suggest ablation types correspond to subsistence procurement groups, as discussed elsewhere (Kusaka et al., 2008, 2011). Future research that focuses on the relationship between tooth ablation and diet would contribute to understanding the meaning of tooth ablation types in the Jomon society.

Conclusions

Strontium isotope ratios were employed to reveal immigrants among the Ota and Tsukumo Jomon skeletal remains by evaluating the statistical coherence of $^{87}Sr/^{86}Sr$ values in tooth enamel. An environmental $^{87}Sr/^{86}Sr$ map was illustrated based on plant $^{87}Sr/^{86}Sr$ values, and regional $^{87}Sr/^{86}Sr$ variations can be explained by the underlying geology. The environmental $^{87}Sr/^{86}Sr$ mapping enabled us to constrain the possible origins of an identified immigrant. The hypothesis that the Late-Final Jomon groups contained more immigrants than the Middle Jomon groups in the Sanyo region was not supported. However, previous research suggested a higher proportion of immigrants in the Late-Final Jomon period in the Tokai region, and further investigations are needed to reveal age differences for migration. The proportion of immigrants between tooth ablation groups did not exhibit a marked difference. This result did not support the hypothesis that type 4I individuals are locals and type 2C individuals are immigrants.

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Table 1. Strontium isotope analysis of Ota samples

No.	Sex	Age at death[a]	M3[b]	$^{87}Sr/^{86}Sr$ in enamel		1 SE	$^{87}Sr/^{86}Sr$ in bone		1 SE
664	F	MAd	LR	0.70895	±	0.000004	-		-
665	F	MAd	UL	0.70889	±	0.000005	-		-
668A	M	Ad	LR	0.70882	±	0.000005	-		-
668B	M	Ad	UL	0.70891	±	0.000005	-		-
670	M	YAd	UL	0.70901	±	0.000006	-		-
674	M	YAd	UR	0.70903	±	0.000005	0.70892	±	0.000005
684	M	YAd	LL	0.70896	±	0.000004	-		-
687	F	YAd	LR	0.70892	±	0.000005	-		-
688	F	YAd	UL	0.70898	±	0.000008	-		-
693	M	YAd	LR	0.70899	±	0.000005	0.70882	±	0.000004
694	M	Ad	LR	0.70888	±	0.000005	-		-
695	M	Ad	LL	0.70882	±	0.000005	-		-
697	F	Ad	LL	0.70855	±	0.000005	0.70884	±	0.000005
702	M	YAd	UL	0.70895	±	0.000004	-		-
709	M	YAd	UR	0.70894	±	0.000006	-		-
710	F	MAd	LR	0.70877	±	0.000005	0.70888	±	0.000005
711	F	YAd	LR	0.70892	±	0.000004	-		-
713	M	Ad	LL	0.70891	±	0.000005	-		-
717	F	YAd	UR	0.70892	±	0.000005	0.70884	±	0.000005
718	M	YAd	LR	0.70893	±	0.000006	-		-
719	M	YAd	UL	0.70897	±	0.000005	-		-
722	F	YAd	LR	0.70887	±	0.000005	-		-
904	F	Ad	UR	0.70894	±	0.000005	-		-

a: AO, adolescent; YAd, young adult; MAd, middle adult; OAd, old adult; Ad, adult.
b: UL, upper left; UR, upper right; LL, lower left; LR, lower right.

Table 2. Strontium isotope analysis of Tsukumo samples

No.	Sex	Age at death[a]	M3[b]	Tooth ablation	$^{87}Sr/^{86}Sr$ in enamel		1 SE	$^{87}Sr/^{86}Sr$ in bone		1 SE
1	F	MAd	LR	4I	0.70896	±	0.000005	-		-
2	M	YAd	LR	2C	0.70894	±	0.000005	-		-
3	M	YAd	LR	4I	0.70885	±	0.000004	-		-
4	F	YAd	LR	4I	0.70915	±	0.000004	0.70897	±	0.000005
5	M	YAd	LR	2C	0.70889	±	0.000005	-		-
6	F	YAd	LR	4I	0.70896	±	0.000005	-		-
7	F	YAd	LR	4I	0.70887	±	0.000005	-		-
8	M	AO	LR	0	0.70889	±	0.000006	-		-
11	F	YAd	LR	4I	0.70911	±	0.000006	-		-
12	F	AO	LL	4I	0.70876	±	0.000006	-		-
13	M	MAd	LR	2C	0.70876	±	0.000004	0.70875	±	0.000005
14	F	YAd	LR	4I	0.70913	±	0.000005	-		-
16	F	YAd	LL	4I	0.70893	±	0.000005	-		-
19	M	YAd	UL	2C	0.70910	±	0.000005	-		-
23	F	YAd	LR	4I	0.70874	±	0.000005	0.70882	±	0.000004
24	M	YAd	LL	2C	0.70888	±	0.000004	-		-
27	M	MAd	LL	0	0.70892	±	0.000005	0.70879	±	0.000005
30	M	YAd	LL	0	0.70886	±	0.000005	-		-
32	M	YAd	UR	2C	0.70901	±	0.000005	-		-
33	M	MAd	LL	2C	0.70925	±	0.000005	0.70879	±	0.000005
34	F	YAd	LL	2C	0.70888	±	0.000005	-		-
37	F	MAd	UR	4I	0.70887	±	0.000004	-		-
39	M	YAd	LL	2C	0.70891	±	0.000005	-		-
40	F	OAd	LL	4I	0.70865	±	0.000005	-		-
41	F	OAd	LL	2C	0.70864	±	0.000005	-		-
42	F	YAd	LL	2C	0.70890	±	0.000004	-		-
44	F	YAd	UR	4I	0.70882	±	0.000005	-		-
46	M	MAd	UL	No ablation	0.70849	±	0.000005	0.70880	±	0.000005
55	M	YAd	LL	2C	0.70896	±	0.000005	-		-
58	M	MAd	LL	0	0.70889	±	0.000004	-		-
65	M	YAd	UR	0	0.70886	±	0.000004	-		-
66	M	YAd	LR	2C	0.70879	±	0.000005	-		-
67	F	MAd	LL	4I	0.70895	±	0.000005	-		-
68	F	YAd	UR	4I	0.70887	±	0.000005	-		-
151	M	MAd	LL	No ablation	0.70881	±	0.000005	-		-
162A	F	MAd	LR	2C	0.70905	±	0.000005	-		-
164	F	YAd	LL	2C	0.70857	±	0.000004	0.70871	±	0.000005

a: See abbreviations of Table 1.
b: See abbreviations of Table 1.

Table 3. Strontium isotope analysis of plants in the study area

No.	Specific name	Common name	Latitude	Longitude	$^{87}Sr/^{86}Sr$		1 SE
OH1	*Quercus glauca*	Ring-cupped Oak	34.44327	133.37527	0.70807	±	0.000005
OH2	*Aucuba japonica*	Japanese Aucuba	34.38665	133.37803	0.70924	±	0.000005
OH3[a]	*Quercus glauca*	Ring-cupped Oak	34.39053	133.31693	0.71037	±	0.000005
OH4[a]	*Machilus thunbergii*	Machilus	34.43465	133.28008	0.70880	±	0.000007
OH5[a]	*Quercus glauca*	Ring-cupped Oak	34.45415	133.22918	0.70857	±	0.000005
OH6[a]	*Ilex rotunda*	Round Leaf Holly	34.42793	133.22547	0.70943	±	0.000005
OH7[a]	*Aucuba japonica*	Japanese Aucuba	34.39622	133.21243	0.70901	±	0.000005
OH8[a]	*Machilus thunbergii*	Machilus	34.37182	133.19980	0.70956	±	0.000005
OH9[a]	*Osmanthus fragrans var. aurantiacus*	Sweet Osmanthus	34.41057	133.19830	0.71026	±	0.000005
OH10[a]	*Quercus glauca*	Ring-cupped Oak	34.39700	133.14867	0.70847	±	0.000004
OH11[a]	*Quercus glauca*	Ring-cupped Oak	34.45533	133.17883	0.71071	±	0.000005
OH12[a]	*Eurya japonica*	Hisakaki	34.43158	133.12975	0.71035	±	0.000005
OH13	*Quercus acutissima*	Sawtooth Oak	34.34320	132.98505	0.71035	±	0.000005
OH14	*Quercus glauca*	Ring-cupped Oak	34.41175	132.99023	0.71002	±	0.000005
OH15	*Quercus glauca*	Ring-cupped Oak	34.46438	133.04955	0.70996	±	0.000006
OH16	*Quercus glauca*	Ring-cupped Oak	34.49343	133.11985	0.70805	±	0.000005
OH17	*Quercus glauca*	Ring-cupped Oak	34.54647	133.18805	0.71065	±	0.000005
OH18	*Cleyera japonica*	Sakaki	34.56968	133.27105	0.70804	±	0.000005
OH19	*Photinia glabra*	Japanese Photinia	34.51765	133.24583	0.70877	±	0.000007
OH20[a]	*Maesa japonica*	Japanese Maesa	34.46955	133.29090	0.70894	±	0.000004
OH21	*Quercus acutissima*	Sawtooth Oak	34.50365	133.36937	0.70994	±	0.000006
OH22[b]	*Quercus glauca*	Ring-cupped Oak	34.49030	133.43530	0.70947	±	0.000005
OH23[b]	*Quercus glauca*	Ring-cupped Oak	34.51825	133.46303	0.70858	±	0.000004
OH24[b]	*Maesa japonica*	Japanese Maesa	34.54950	133.49827	0.70938	±	0.000005
OH25[b]	*Quercus glauca*	Ring-cupped Oak	34.55557	133.55377	0.70780	±	0.000007
OH26[b]	*Quercus glauca*	Ring-cupped Oak	34.52612	133.52978	0.70976	±	0.000005
OH27[b]	*Pieris japonica*	Japanese Andromeda	34.51992	133.50942	0.71014	±	0.000005
OH28[b]	*Quercus glauca*	Ring-cupped Oak	34.48478	133.53403	0.70898	±	0.000005
OH29[b]	*Cerasus sp.*	Chelly Blossom	34.45332	133.50515	0.70867	±	0.000008
OH30[b]	*Elaeagnus pungens*	Nawashirogumi	34.46485	133.55352	0.70946	±	0.000005
OH31[b]	*Elaeocarpus sylvestris*	Horutonoki	34.47910	133.57730	0.70926	±	0.000005
OH32[b]	*Quercus glauca*	Ring-cupped Oak	34.52400	133.59845	0.70991	±	0.000005
OH33	*Quercus glauca*	Ring-cupped Oak	34.55225	133.62717	0.70829	±	0.000004
OH34	*Quercus glauca*	Ring-cupped Oak	34.59027	133.70602	0.70859	±	0.000005
OH35	*Dendropanax trifidus*	Kakuremino	34.61472	133.67605	0.70841	±	0.000005
OH36	*Quercus glauca*	Ring-cupped Oak	34.61638	133.62730	0.70792	±	0.000004

OH37	*Quercus glauca*	Ring-cupped Oak	34.65702	133.55007	0.70696	±	0.000004
OH38	*Quercus glauca*	Ring-cupped Oak	34.60205	133.53387	0.70798	±	0.000005
OH39	*Aucuba japonica*	Japanese Aucuba	34.60290	133.45870	0.70927	±	0.000006
OH40	*Aucuba japonica*	Japanese Aucuba	34.64052	133.42448	0.70770	±	0.000004
OH41	*Maesa japonica*	Japanese Maesa	34.57252	133.40638	0.70879	±	0.000005
OH42	*Quercus glauca*	Ring-cupped Oak	34.58437	133.34072	0.70882	±	0.000005

a: Samples collected within the radius of 10 km from the Ota site.
b: Samples collected within the radius of 10 km from the Tsukumo site.

Table 4. Descriptive statistics for $^{87}Sr/^{86}Sr$ ratios in human enamel in Ota's "all" and "local" data sets and Tsukumo's "all" data set.

Statistic	Ota all data	Ota local data	Tsukumo all data
N	23	22	37
Mean	0.70891	0.70892	0.70889
SD	0.00010	0.00006	0.00016
Maximum	0.70903	0.70903	0.70925
Minimum	0.70855	0.70877	0.70849
Median	0.70893	0.70893	0.70889
Skewness (standard error)	−2.31 (0.48)	−0.72 (0.49)	−0.18 (0.39)
Kurtosis (standard error)	7.28 (0.93)	0.67 (0.95)	0.86 (0.76)
Coefficient of variation	0.01402	0.00884	0.02196

Figures

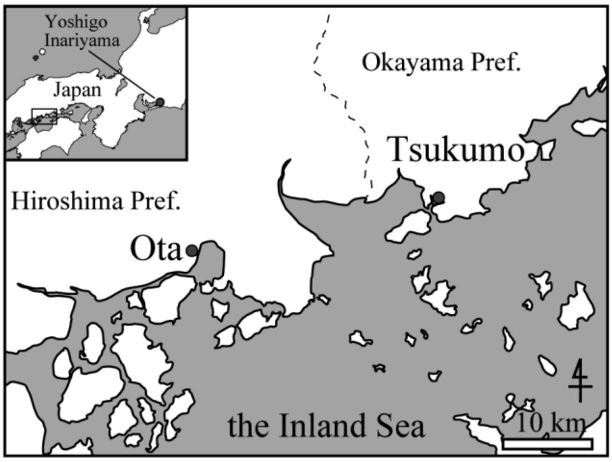

Fig. 1. Map of the study area showing the location of the Ota, Tsukumo, Yoshigo, and Inariyama shell mounds.

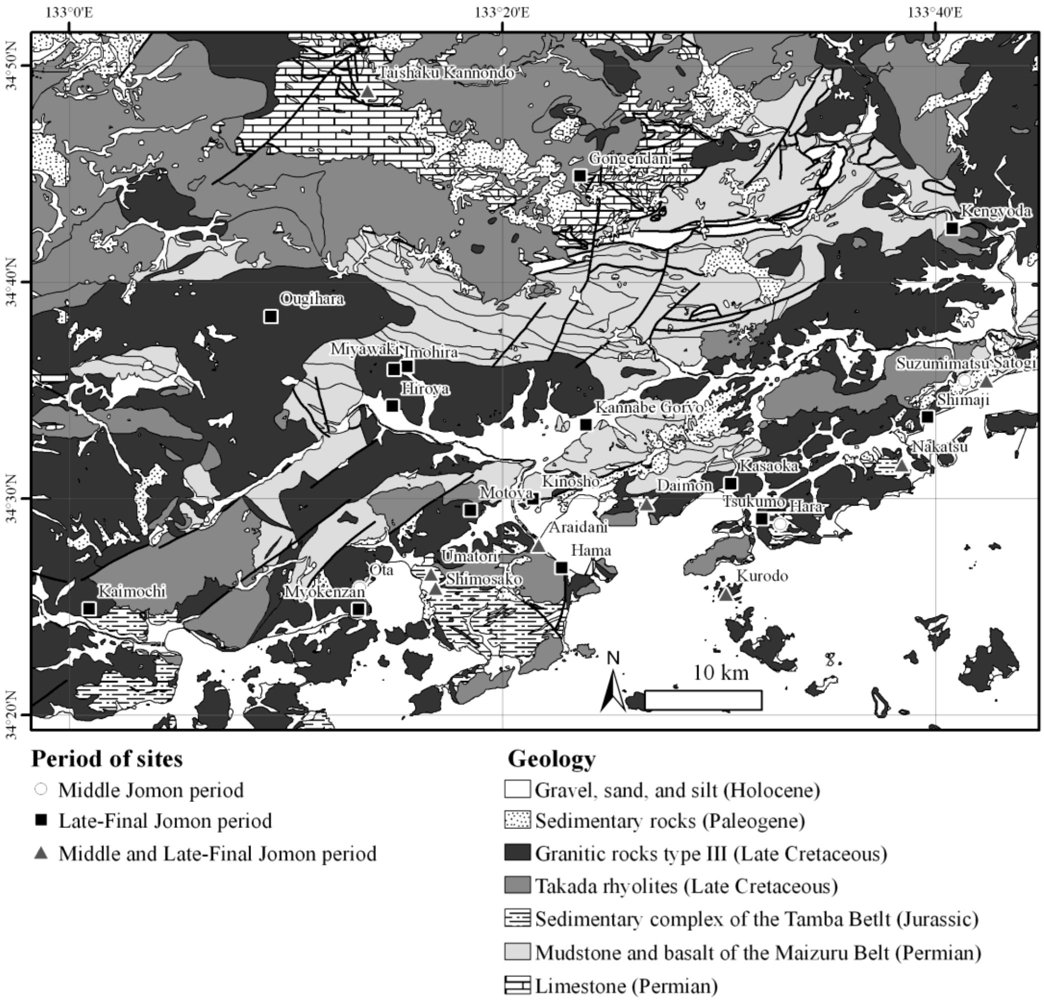

Fig. 2. Geologic map of the study area, modified from the 1:200,000 integrated geologic map (Geological Survey of Japan, AIST, 2005), and Jomon sites divided by period modified from Okamoto (1987), Hirai (1987), and Kawase (2006).

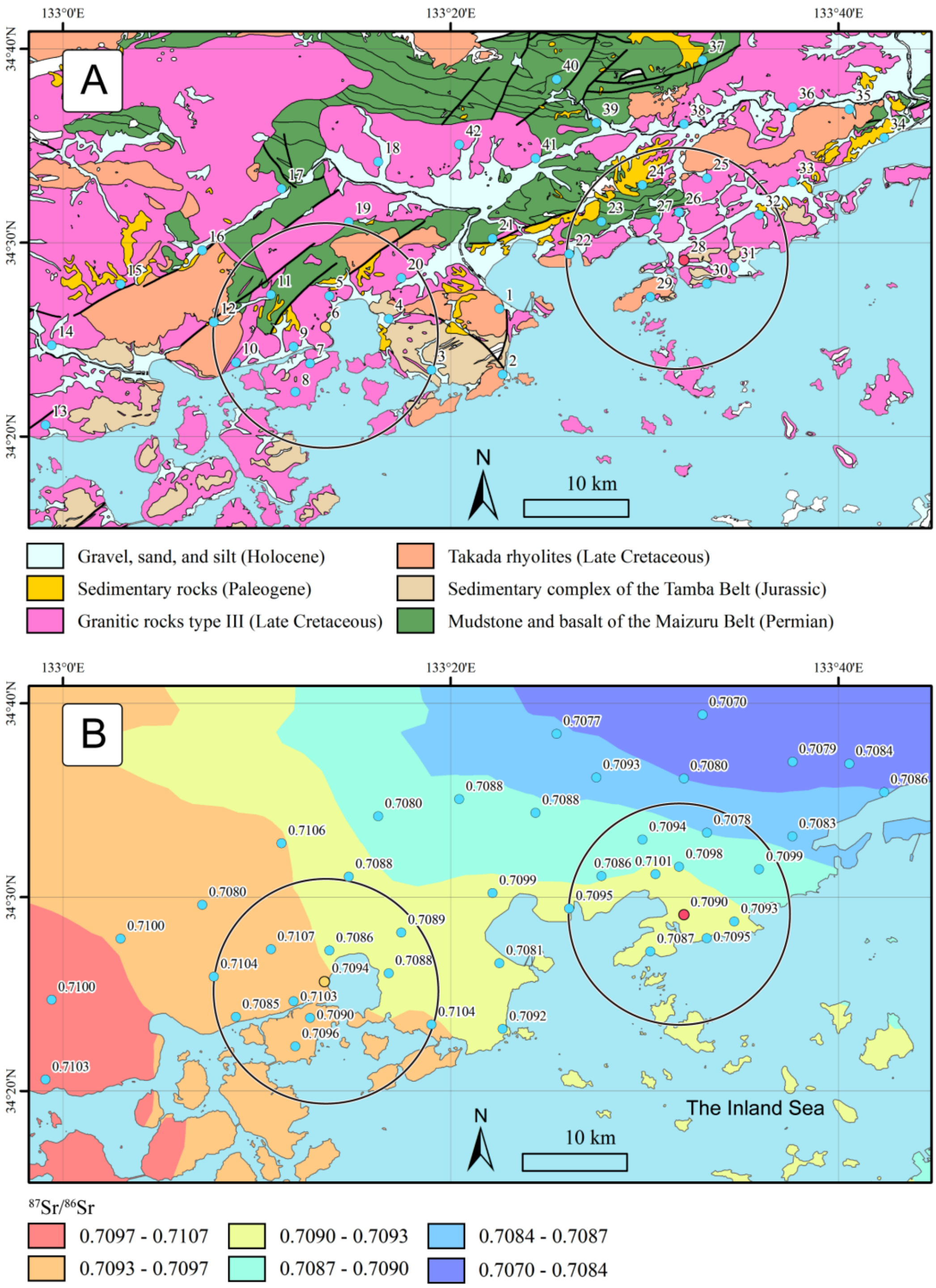

Fig. 3. (A) Geologic map of the study area. Open circles indicate plant-sampling locations with sample numbers. Circles No. 6 and No. 28 indicate the Ota and Tsukumo sites, respectively. Large circles indicate 10 km range from the sites. (B) Map of the geographic distribution of strontium isotope ratios in plants. The graphic representation was performed using ArcGIS (ESRI, Inc.) software and the kriging calculation method.

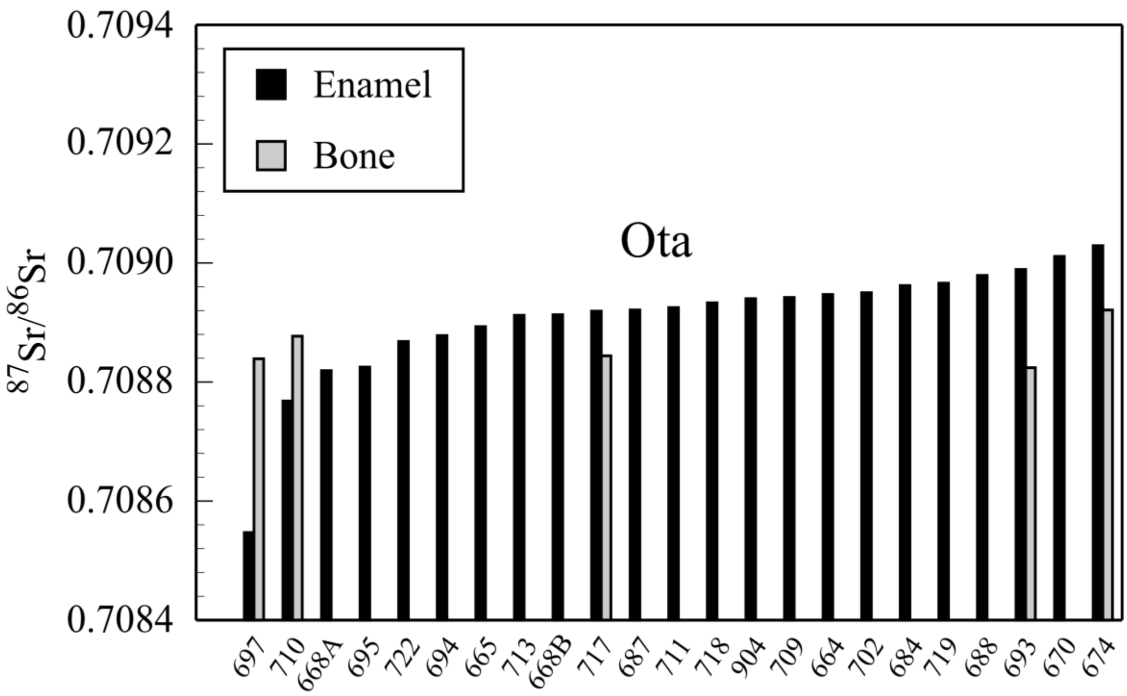

Fig. 4. Strontium isotope ratios in human tooth enamel and bone of the Ota skeletal remains. The values are arranged in rank order. Black bars are tooth enamel samples, and gray bars are bone samples.

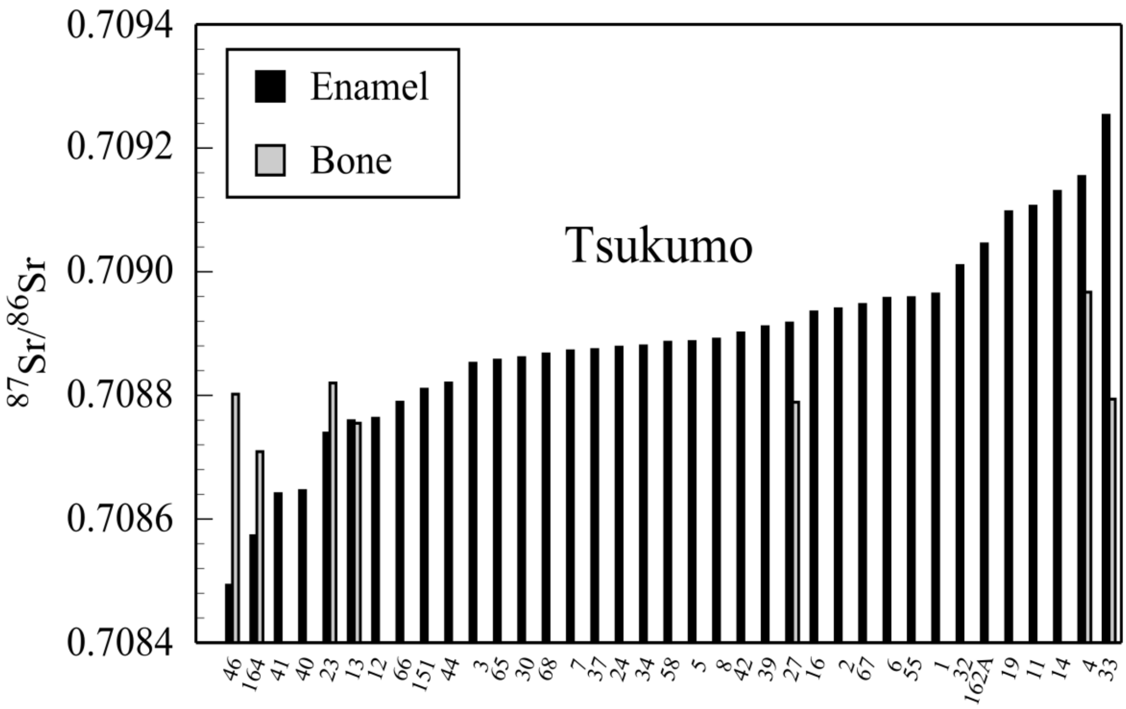

Fig. 5. Strontium isotope ratios in human tooth enamel and bone of the Tsukumo skeletal remains. The values are arranged in rank order. Black bars are tooth enamel samples, and gray bars are bone samples.

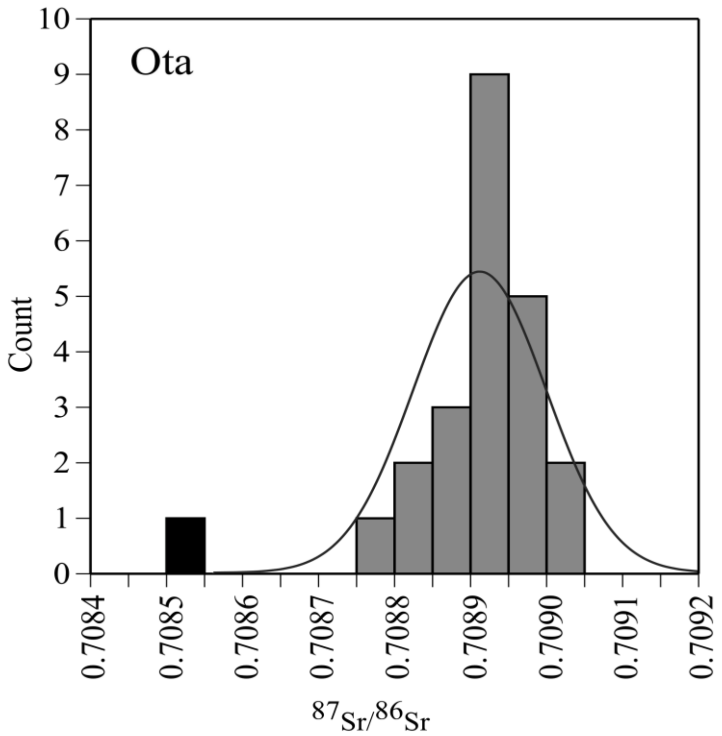

Fig. 6. Histogram of the “all” data set from Ota with a normal distribution curve for comparison. The black sample indicates an outlier.

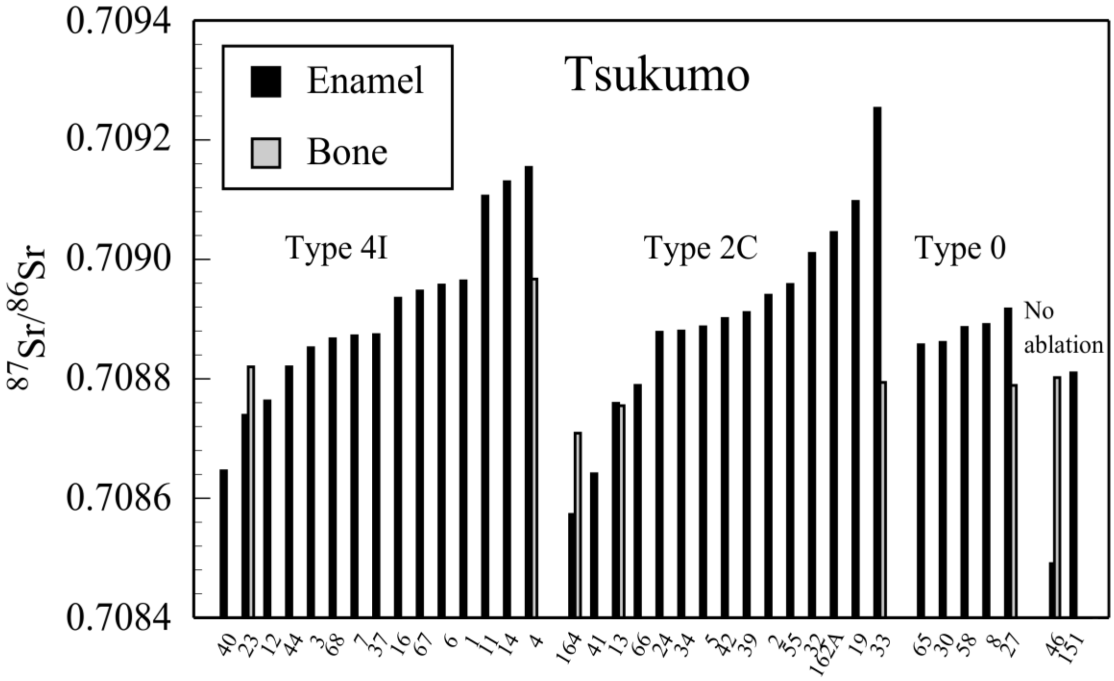

Fig. 7. Strontium isotope ratios in human tooth enamel and bone of the Tsukumo skeletal remains, categorized by ritual tooth ablation type. The values are arranged in rank order for each category. Black bars are tooth enamel samples, and gray bars are bone samples.